

A Practical Guide to Shaft Alignment

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The purpose of producing this handbook is to provide basic information and guidelines for the implementation of good shaft alignment for standard rotating machine systems.

Laser alignment is an essential component of a viable maintenance strategy for rotating machines. In isolation each strategy can help to reduce unexpected machine failure but taken together they form the hub of a proactive maintenance strategy that will not only identify incipient problems but allows extending machine operating life considerably.

In each section of this handbook we have used one or two examples of the available methods for measuring the required parameters. We do not suggest that the methods illustrated are the only ones available.

Prueftechnik are specialists in the alignment and monitoring of rotating machines, we have accumulated substantial practical knowledge of these subjects over the 30 years of our existence, in so doing we have produced many handbooks covering individual subjects and systems. This handbook is a distillation of this accumulated knowledge plus a brief overview in each section of the latest systems from Prueftechnik that address the specific applications concerned.

We hope that this information is presented in a clear readable form and that it will provide for the reader new to the subject a platform to successfully apply profitable maintenance practice in their plant.


We are indebted to our colleagues in Prueftechnik AG (Germany) and our associates at LUDECA Inc. (USA) for permission to reproduce some of the graphics used in this handbook, additionally we have drawn on information previously published in Prueftechnik equipment handbooks for information on alignment standards, and graphical and mathematical methods of balance calculation. For this information we are grateful.

Shaft Alignment

	Page Number
What is shaft alignment	6
.. A definition	6
.. Machine catenary	7
.. Operation above critical speed	8
Expressing alignment	10
.. Alignment parameters	10
.. Angularity, gap and offset	11
.. Short flexible couplings	14
.. Spacer shafts	15
How precise should alignment be?	18
.. Alignment tolerances	18
Troubleshooting	21
.. Coupling strain and shaft deflection	21
Causes of machine breakdown	23
.. Couplings and misalignment	23
.. Bearings	24
.. Seal wear	24
.. Machine vibration	25
.. Symptoms of misalignment	25
Alignment methods and practice	27
.. Machine installation guidelines	28
.. Measurement and correction of soft foot	29
Alignment by Eyesight	33


	Page Number
Alignment by Dial indicator	36
.. Trial and error method	37
.. Rim and face method - by calculation	38
.. Reverse indicator method - by calculation	41
.. Indicator bracket sag measurement	43
Alignment by Laser	45
.. Basic operation requirements	48
Laser alignment case study	
.. Laser alignment cuts energy costs	52
.. Laser alignment improves pump reliability	56
.. Laser alignment improves bearing & seal life	58
.. Laser alignment reduces vibration alarms	59
Thermal expansion of machines	60
.. Thermal growth calculations	61

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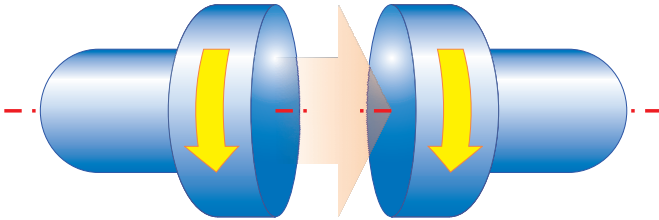
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Shaft Alignment

What is shaft alignment?

A Definition

Shaft alignment is the process whereby two or more machines (typically a motor and pump) are positioned such that at the point of power transfer from one shaft to another, the axes of rotation of both shafts should be colinear when the machine is running under normal conditions.



As with all standard definitions there are exceptions. Some coupling types, for example gear couplings or cardan shafts, require a defined misalignment to ensure correct lubrication when operating.

The important points to note in the above definition are.

At the point of power transfer...

All shafts have some form of catenary due to their own weight, thus shafts are not straight, therefore the location where the alignment of the two shafts can be compared is only at the point of power transfer from one shaft to the next.

...the axes of rotation...

Do not confuse “shaft alignment” with “coupling alignment”. The coupling surfaces should not be used to define alignment condition since they do not represent the rotation axis of the shafts.

What is shaft alignment?

The accuracy of the fit of the coupling on the shaft is unknown

Rotating only one shaft and using dial gauges to measure the opposing coupling surface does not determine the axis of rotation of both shafts.

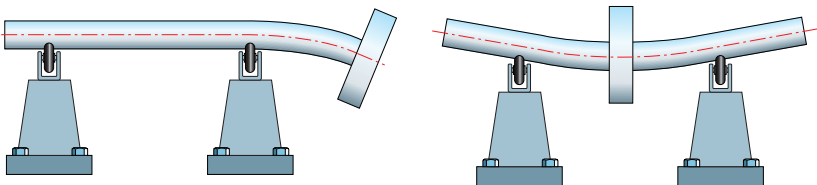
... under normal operating conditions

The alignment condition can change when the machine is running. This can be for a number of reasons including thermal growth, piping strain, machine torque, foundation movement and bearing play. Since shaft alignment is usually measured with the machines cold, the alignment condition as measured is not necessarily the zero alignment condition of the machines. (see page 60 - 62)

Alignment condition should be measured while turning the shafts in the normal direction of rotation. Most pumps, fans and motors etc. have arrows on the end casing showing direction of rotation.

Machinery catenary

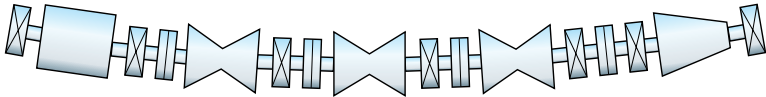
The amount of shaft deflection in a machine depends upon several factors such as the stiffness of the shafts, the amount of weight between overhanging supports, the bearing design and the distance between the supports.



The natural deflection of shafts under their own weight

What is shaft alignment?

For the vast majority of close coupled rotating machines this catenary bow is negligible, and therefore for practical purposes can be ignored. On long drive machine trains, e.g. turbine generators in power generation plants or machines with long spacer shafts e.g. cooling tower fans or gas turbines, the catenary curve must be taken into consideration.

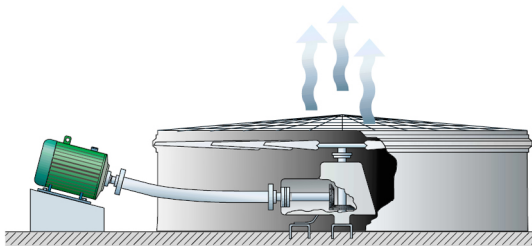


Machine catenary

In a steam turbine for example the shafts are usually aligned to each other better than 4 mils, but the mid point of the center shaft could be as much as 1.2 inches lower than the two end shafts.

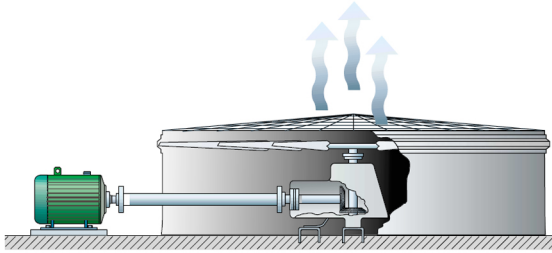
Operation above critical speed?

When a very long, flexible shaft begins to rotate, the bow of the shaft tries to straighten out, but will never become a perfectly straight line. It is important to understand that the axis of rotation of a shaft could very possibly run on a curved axis of rotation. In situations where two or more pieces of machinery are coupled together with one or more shafts rotating around a catenary shaped axis of rotation, it is important to align the shafts so that they maintain the curved centerline of rotation.



Drive shaft operation below critical speed:
Align machine couplings to spacer couplings

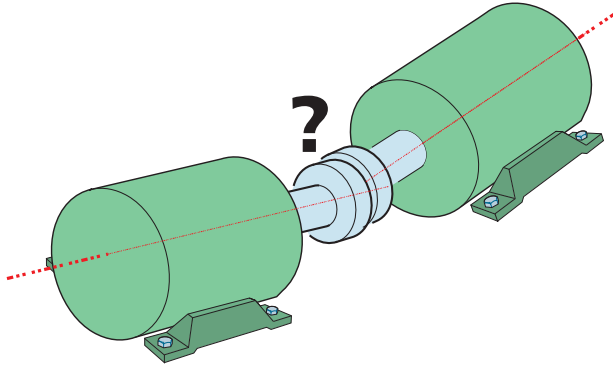
What is shaft alignment?



Drive shaft operation above critical speed:
Align machine couplings to one another ignoring spacer.

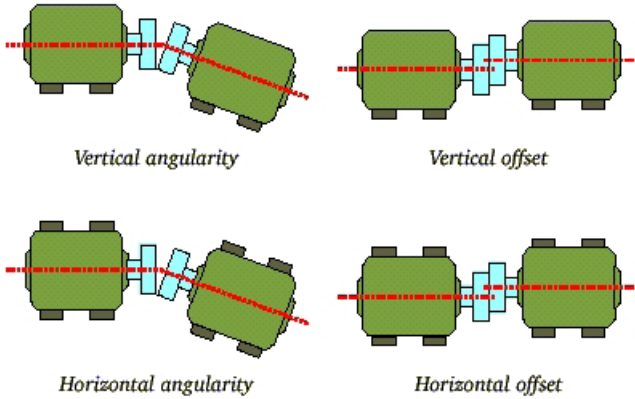
Alignment parameters

Since shaft alignment needs to be measured and subsequently corrected, a method of quantifying and describing alignment condition is necessary.



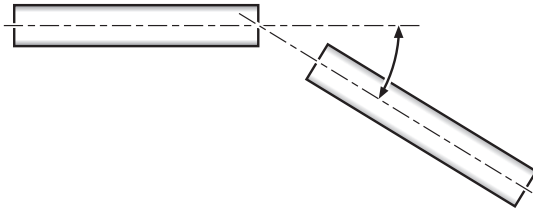
Traditionally alignment has been described in terms of dial indicator readings at the coupling face or position values at the machine feet. The measured values from both of these methods are dependent upon the dimensions of the machines. Since there are many different methods for mounting dial indicators (reverse indicator, rim and face, double rim for example) the comparison of measurements and the application of tolerances can be problematic. Additionally the fact that rim indicator readings show twice the true offset and sign reversals must be observed depending on whether the indicator measures an internal or external, left or right coupling face or rim.

A more modern and easily understandable approach is to describe machine alignment condition in terms of **angularity** and **offset** in the horizontal (plan view) and vertical (side view). Using this method four values can then be used to express alignment condition as shown in the following diagram.



Angularity, gap and offset

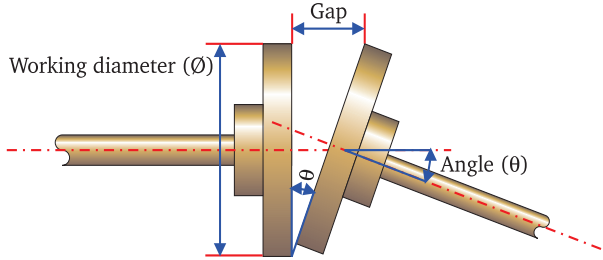
Angularity describes the angle between two rotating axes.



Angularity can be expressed directly as an angle in degrees or in terms of a slope in mils/inch. This latter method is useful since the angularity multiplied by the coupling diameter gives an equivalent gap difference at the coupling rim.

Thus the angle is more popularly expressed in terms of GAP per diameter. The gap itself is not meaningful, it must be divided by the diameter to have meaning. The diameter is correctly referred to as a “working diameter”, but is often called a coupling diameter. The working diameter can be any convenient value. It is the relationship between gap and diameter that is important.

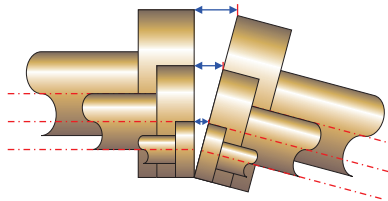
Expressing alignment



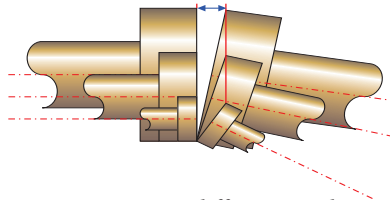
Relationship of angle, gap and working diameter.

A 6 inch coupling open at the top by 5.0 mils gives an angle between shafts axes of 0.83 mils per inch.

For a 10 inch working diameter this corresponds to a gap of 8.3 mils per 10 inches.



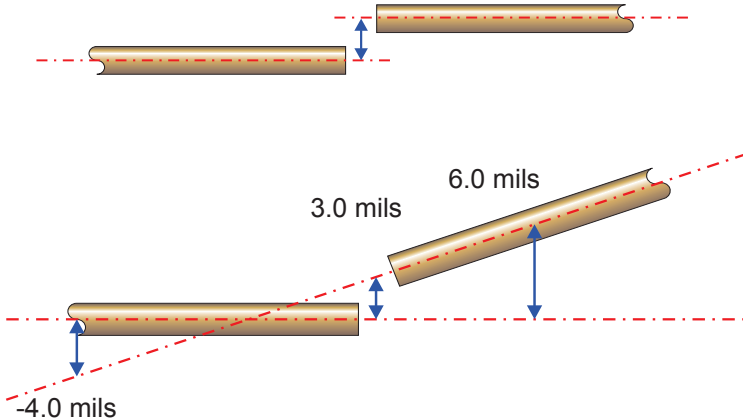
same angle - different gap



same gap - different angle

Expressing alignment

Offset describes the distance between rotation axes at a given point. Offset is sometimes incorrectly referred to as parallel offset or rim misalignment, the shaft rotation axes are however rarely parallel and the coupling or shaft rim has an unknown relationship to the shaft rotation axes.



As shown above, for the same alignment condition, the offset value varies depending upon the location where the distance between two shaft rotation axes is measured. In the absence of any other instruction, offset is measured in mm or thousandths of an inch at the coupling center. (This definition refers to short flexible couplings, for spacer couplings offset should be measured at the power transmission planes of the coupling).

Short Flexible couplings

For ease of understanding we define short flexible couplings when **the axial length of the flexible element or the axial length between the flexible element is equal to or smaller than the coupling diameter**. Machines with short flexible couplings running at medium to high speed require very accurate alignment to avoid undue loading of the shafts, bearings and seals.

Since the alignment condition is virtually always a combination of angularity and offset, and the machine has to be corrected in both vertical and horizontal planes, 4 values are required to fully describe the alignment condition.

Vertical angularity (or gap per diameter)

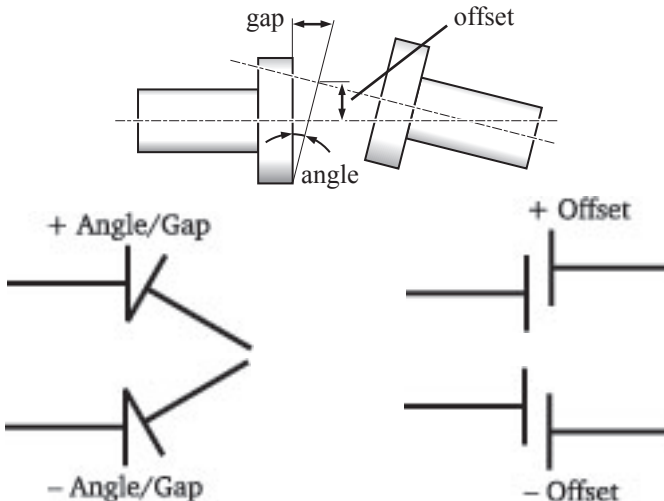
Vertical offset

Horizontal angularity (or gap per diameter)

Horizontal offset.

Unless otherwise specified the offset refers to the distance between shaft rotation axes at the coupling center.

The sketch below shows the notation and sign convention.



Spacer Shafts

Spacer shafts are usually installed when significant alignment changes are anticipated during operation of the machine, for example due to thermal growth. Through the length of the spacer shaft, the angular change at the spacer shaft end remains small even when larger machine positional changes occur. The alignment precision for machines fitted with spacer shafts that have flexible elements at each end is not as critical as for machines that have short flexible couplings installed.

Four values are required to fully describe the alignment condition.

Vertical angle a

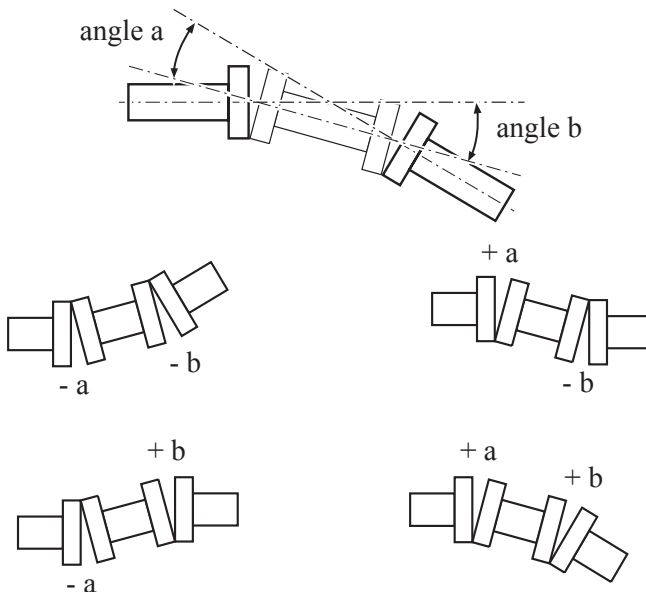
Vertical angle b

Horizontal angle a

Horizontal angle b

Angles are measured between the spacer shaft rotation axis and the respective machine rotation axes.

The sketch below shows notation and sign convention



Offset B - offset A

As an alternative to the 2 angles a and b the alignment can be specified in terms of offsets.

Vertical offset b

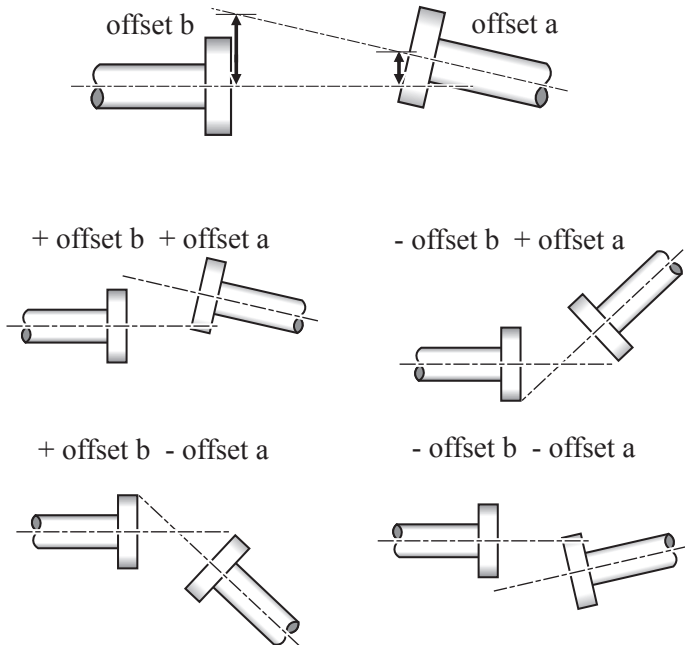
Vertical offset a

Horizontal offset b

Horizontal offset a

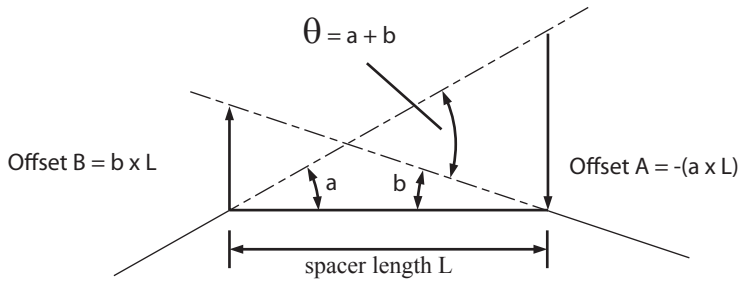
The offsets are measured between the machine shaft rotation axes at the location of the spacer shafts ends. This is similar to reverse indicator alignment.

The sketch shows the notation and sign convention.



Relationships

By studying the diagram below a clearer understanding of the relationship between the various offsets and angles will be obtained.



How precise should alignment be?

Alignment tolerances for flexible couplings

The suggested tolerances shown on the following pages are general values based upon over 20 years of shaft alignment experience at Prueftechnik and should not be exceeded. They should be used only if no other tolerances are prescribed by existing in-house standards or by the machine manufacturer.

Consider all values to be the maximum allowable deviation from the alignment target, be it zero or some desired value to compensate for thermal growth. In most cases a quick glance at the table will tell whether coupling misalignment is allowable or not.

As an example, a machine with a short flexible coupling running at 1800 RPM has coupling offsets of -1.6 mils vertically and 1.0 mil horizontally, both of these values fall within the “excellent” limit of 2.0 mils.

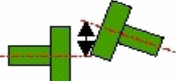
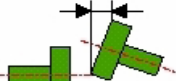

Angularity is usually measured in terms of gap difference. For a given amount of angularity, the larger the diameter the wider the gap at the coupling rim (see page 12). The following table lists values for coupling diameters of 10 inches. For other coupling diameters multiply the value from the table by the appropriate factor. For example, a machine running at 1800 RPM has a coupling diameter of 3 inches. At this diameter the maximum allowable gap would be: 0.9 mils.

For spacer shafts the table gives the maximum allowable offset for 1 inch of spacer shaft length. For example, a machine running at 1800 RPM with 12 inch of spacer shaft length would allow a maximum offset of: 0.6 mils/inch x 12 inches = 7.2 mils at either coupling at the ends of the spacer shaft.

Rigid couplings have no tolerance for misalignment, they should be aligned as accurately as possible.

How precise should alignment be?

Suggested alignment tolerance table

	RPM	metric (mm)		Inch (mils)	
		Acceptable	Excellent	Acceptable	Excellent
Short "flexible" couplings Offset: 	600			9.0	5.0
	750	0.19	0.09		
	900			6.0	3.0
	1200			4.0	2.5
	1500	0.09	0.06		
	1800			3.0	2.0
	3000	0.06	0.03		
	3600			1.5	1.0
	6000	0.03	0.02		
	7200			1.0	0.5
Angularity Metric values—Gap difference per 100 mm coupling diameter Inch values—Gap difference per 10 inch coupling diameter 	600			15.0	10.0
	750	0.13	0.09		
	900			10.0	7.0
	1200			8.0	5.0
	1500	0.07	0.05		
	1800			5.0	3.0
	3000	0.04	0.03		
	3600			3.0	2.0
	6000	0.03	0.02		
	7200			2.0	1.0
Spacer shafts and membrane (disc) couplings Metric values—Offset per 100 mm spacer shaft Inch values—Offset per inch spacer length 	600			3.0	1.8
	750	0.25	0.15		
	900			2.0	1.2
	1200			1.5	0.9
	1500	0.12	0.07		
	1800			1.0	0.6
	3000	0.07	0.04		
	3600			0.5	0.3
	6000	0.03	0.02		
	7200			0.3	0.2
Soft-foot	Any		0.06		2

How precise should alignment be?

Note

For industrial equipment the amount of misalignment that can be tolerated is a function of many variables including RPM, power rating, coupling type, spacer length, design of coupled equipment and expectations of the user with respect to service life. Since it is not practical to consider all these variables in a reasonably useful alignment specification, some simplification of tolerances is necessary.

Tolerances based on RPM and coupling spacer length were first published in the 1970's. Many of the tolerances were based primarily on experience with lubricated gear type couplings. Experience has shown however that these tolerances are equally applicable to the vast majority of non lubricated coupling systems that employ flexible elements in their design.

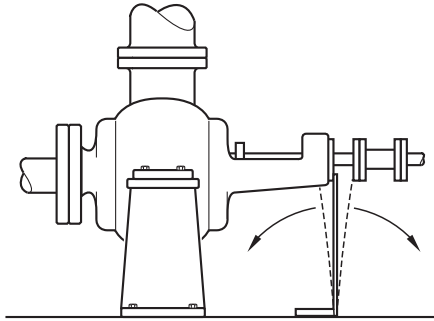
In the previous table "acceptable" limits are calculated from the sliding velocity of lubricated steel on steel, using a value of 0.5 inch/sec for allowable sliding velocity. Since these values also coincide with those derived from elastomer shear rates they can be applied to short flexible couplings with flexible elements.

"Excellent" values are based on observation made on a wide variety of machines to determine critical misalignment for vibration. Compliance with these tolerances does not however guarantee vibration free operation.

Coupling strain and shaft deflection

New readings do not agree with moves just made?

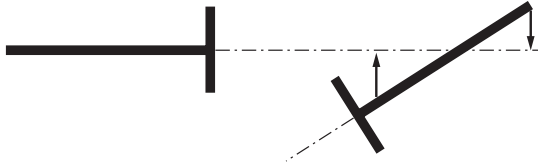
When performing an alignment whether using dial indicators or laser optical systems, sometimes the readings following an alignment adjustment do not agree with the corrections made. One possibility is that coupling strain is deflecting the shaft, the machine mounts or the foundation. This has frequently been noticed particularly on pump sets which have a front “steady” mount as shown in the following sketch.



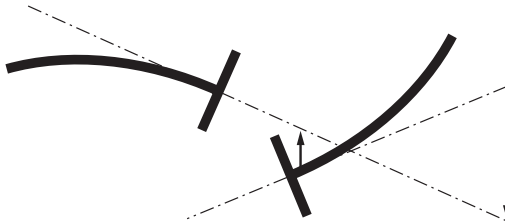
In this application the flexible coupling element is radially quite rigid and can influence the alignment measurement. In this situation we advise splitting the coupling element to free the measured alignment from such external forces.

If not accommodated the net effect of influences such as noted above is that the new alignment is not only wrong but quite often has been made in the opposite direction to the required alignment correction.

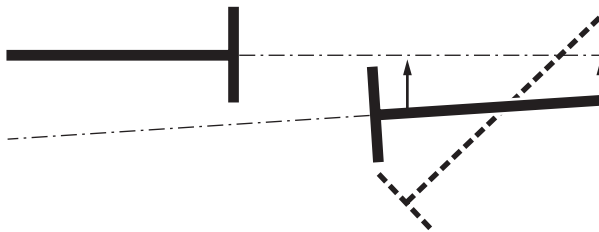
In extreme cases coupling strain imposed by the newly aligned machines can bend shafts during operation. In most cases this bending will be minimal but sufficient to affect the measured axes of shaft rotation. The following sketches illustrate the potential problem.



This is the alignment condition with shafts uncoupled



This is the measured alignment with the shafts coupled.
Projected centerlines of rotation are shown

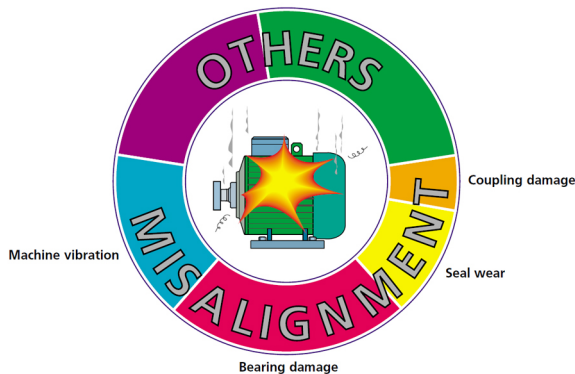


The moves are made as measured. There is less strain on the coupling now and the shafts can be properly aligned at the next attempt.

Couplings can take misalignment?

An often quoted comment is “...why bother to align the machine when it is fitted with a flexible coupling designed to take misalignment?”

Experience and coupling manufacturers’ maximum misalignment recommendations would suggest otherwise. Anecdotal evidence suggests that as much as 50% of machine breakdowns can be directly attributed to incorrect shaft alignment.



It is true that flexible couplings are designed to take misalignment, typically up to 400 mils or more radial offset of the shafts. But the load imposed on shafts, and thus the bearings and seals increase dramatically due to the reaction forces created within the coupling when misaligned.

Anti-friction Bearings

Bearings are precision manufactured components designed to operate with clean lubrication and constant but restricted operating temperatures. Components manufactured within 0.2 mils accuracy are:

- Not able to withstand operating for long periods at elevated temperatures caused by misalignment.
- Not able to withstand contamination caused by mechanical seal failure which has allowed ingress of dirt, grit, metallic elements or other objects.
- Not manufactured to operate for long periods with misalignment imposing axial shock loads on the carefully machined and honed components.

In addition to the damage imposed on the bearings through the misalignment itself, when mechanical seals fail, bearings have to be removed from the shaft assembly, sometimes re-fitted or in most cases replaced. Removal and re-fitting in itself can cause bearing damage. Most pump manufacturers and repairers recommend that when repairing damaged pumps, bearings should always be replaced irrespective of apparent condition, since it is easy to miss minor damage to the bearing that will progressively worsen after re-fitting.

Mechanical Seals

Seal wear increases due to shaft loading when shafts are misaligned. Pump seals are a high cost item often costing up to a third of the total pump cost. Poor installation and excessive shaft misalignment will substantially reduce seal life. Manufacturers have addressed the problem of poor installation practice by the introduction of cartridge type seals which can be installed with little or no site assembly. Seals however have precision ground and honed components with finished accuracy of 2 microns (0.08 mils) they do not tolerate operation in a poorly aligned condition, face rubbing, elevated temperatures and ingress of contaminants quickly damage expensive components. Seal failure is often catastrophic, giving little or no pre warning, the resultant plant downtime, seal replacement costs, pump repair costs and bearing replacements makes seal failure due to misalignment an expensive and unnecessary problem.

Machine vibration

Machine vibration increases with misalignment. High vibration leads to fatigue of machine components and consequently to premature machine failure.

The accumulated benefits of shaft alignment

The benefits that accrue from adopting good shaft alignment practice begin with improved machine operating life thus ensuring plant availability when production requires it. Accurately aligned machinery will achieve the following results.

- Improve plant operating life and reliability
- Reduce costs of consumed spare parts such as seals and bearings
- Reduce maintenance labor costs
- Improve production plant availability
- Reduce production loss caused by plant failure
- Reduce the need for standby plant
- Improve plant operating safety
- Reduce costs of power consumption on the plant
- “Push” plant operation limits in times of production need
- Obtain better plant insurance rates through better operating practice and results

Symptoms of misalignment

It is not always easy to detect misalignment on machinery that is running. The radial forces that are transmitted from shaft to shaft are difficult to measure externally. Using vibration analysis or infrared thermography it is possible to identify primary symptoms of misalignment such as high vibration readings in radial and axial directions or abnormal temperature gradients in machine casings, but without such instrumentation it is also possible to identify secondary machine problems which can indicate inaccurate shaft alignment.

Causes of machine breakdown

- Loose or broken foundation bolts.
- Loose shim packs or dowel pins.
- Excessive oil leakage at bearing seals.
- Loose or broken coupling bolts.
- Some flexible coupling designs run hot when misaligned. If the coupling has elastomeric elements look for rubber powder inside the coupling shroud.
- Similar pieces of equipment are vibrating less or have longer operating life.
- Unusual high rate of coupling failures or wear.
- Excessive amount of grease or oil inside coupling guards.
- Shafts are breaking or cracking at or close to the inboard bearings or coupling hubs.

Good shaft alignment practice should be a key strategy in the maintenance of rotating machines. A machine properly aligned will be a reliable asset to the plant, it will be there when it is needed and will require less scheduled (and unscheduled) maintenance. In a later section we will review some specific case studies that will show how shaft alignment will deliver substantial cost benefits to operating plants. The next section of this handbook however will review the various methods of shaft alignment that can be used to deliver good installed machinery alignment.

There are a number of different methods whereby acceptable rotating machine alignment can be achieved. These range from an inexpensive straight edge to the more sophisticated and inevitably more expensive laser systems. We can condense these methods into three basic categories,

- Eyesight – straightedge and feeler gauges
- Dial indicators – mechanical displacement gauges
- Laser optic alignment systems

Within each category there are a number of variations and options, it is not the intention here to evaluate all of these options, instead we will concentrate on the most widely used methods in each category.

Preparation is important

The first preparatory step toward successful alignment is to ensure that the machine to be aligned may be moved as required: this includes vertical mobility upwards (using proper lifting equipment, of course) and downwards, should the machine require lowering, as is frequently the case. This can be achieved by inserting 2 to 4 mm (0.08" - 0.16") of shims beneath the feet of both machines on initial installation (we recommend shimming both machines initially so that changes in the foundation condition may later be compensated, if need be).

Horizontal positioning of machines is best performed using jack bolts or a simple 'machine puller' tool or hydraulic equipment, all of which allow fine control of movement in a slow, gentle and continuous manner. Methods such as hammers not only make exact positioning more difficult but can damage machines (by causing chatter marks on bearings), but the vibration could displace the alignment system during the MOVE function and therefore lead to less accurate monitoring of correction positioning.

Machine installation guidelines

The installation of machinery such as a pump, gearbox or compressor etc. require some general rules to be followed.

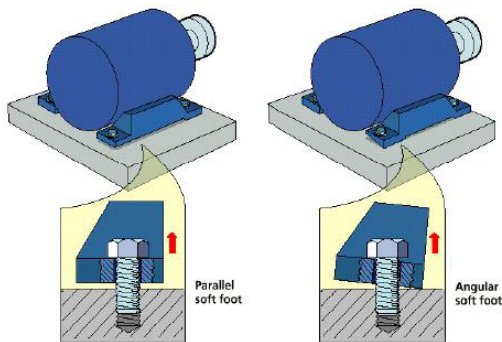
- The driven unit is normally installed first, and the prime mover or motor is then aligned to the shaft of the driven unit.
- If the driven unit is driven through a gearbox, then the gearbox should be aligned to the driven unit and the driver aligned to the gear box.
- Basic checks should be carried out to determine the accuracy of the machine couplings, i.e. check for “run-out” (concentricity and squareness to the shaft centerlines) of coupling halves using a dial indicator, if possible (out of “true” coupling halves can cause out of balance problems!).
- Preparation of the machinery baseplate and machine mounting surfaces, feet, pedestals etc. is of paramount importance! Successful alignment cannot be easily achieved otherwise!
- Clean, dress up and file any burrs from mounting faces and anchor bolt holes etc.
- Have quality precut shims available to align precisely and effectively.
- Before assembling the shaft alignment system/ instrumentation to the machines, take a few minutes to look at the coupling/shaft alignment. Remember, your eyes are your first measuring system!
- Check that the pump/motor etc. is sitting square to the base plate. (Soft foot check) and correct as required - see following pages.
- Keep shims to a minimum i.e. no more than 3 shims maximum if possible under machinery feet/mounts.
- Correct alignment as required to ensure that, when the machinery is running, the machinery shafts are centered in their bearings and are aligned to manufacturers’ tolerances.

Alignment methods and practices

- Always check manufacturers alignment figures prior to commencing work! - temperature growth may require specific “cold” alignment offsets.
- Ensure that any pipework attached to machines is correctly supported but free to move with thermal expansion.

Measurement and correction of soft foot

An essential component of any successful alignment procedure is the determination and correction of soft foot. Just as a wobbly chair or table is an annoyance, a wobbly machine mount causes alignment frustration. The machine stands differently each time an alignment is attempted, and each set of readings indicate that the machine is still misaligned. Additionally when the machine is bolted down, strain is placed upon the machine casing and bearing housings. Essentially, there are three types of soft foot, two of which are illustrated in the sketch below.



Parallel soft foot indicates that the baseplate and machine foot are parallel to each other allowing correction by simply adding shims of the correct thickness. Angular soft foot is caused by the machine feet forming an angle between each other. This situation is more complex to diagnose and to correct. One solution is to use tapered shims to fill the angular space between the baseplate and the foot; a more drastic but long term solution is to remove the machine and grind the machine feet flat (or correct the angle of the baseplate)

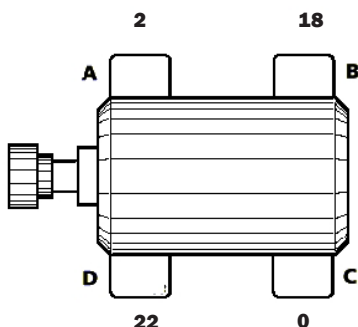
Alignment methods and practices

Soft foot measurement

Using a variety of techniques, soft foot can be determined prior to alignment commencing.

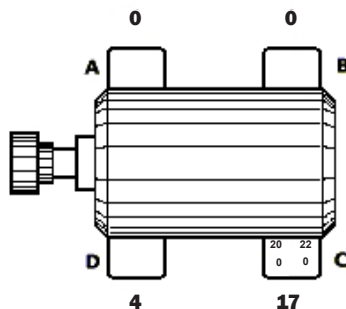
Using a laser alignment system loosen one machine foot at a time the alignment system calculates the amount of foot lift at each foot. Retighten the machine foot before proceeding to the next foot.

Having determined the amount of soft foot present as indicated below it is possible to make adjustments to the machine according to the soft foot condition diagnosed.

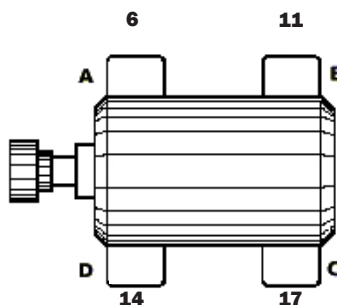


This example shows classic soft foot problems with a rock across feet B and D. It is tempting to shim both feet to eliminate the rock but this would be a mistake. The best solution would be to shim only the foot with the highest value and recheck all four feet.

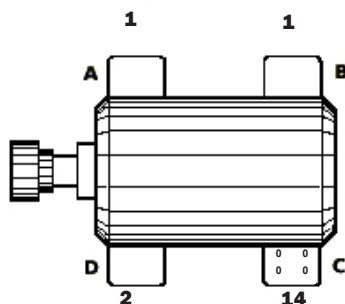
Many additional soft foot problems may be found including bent feet, strain imposed by pipe work or “squishy foot” caused by too many shims under the machine feet. Some examples are shown in the following sketches.



Soft foot example: bent foot - step shim at foot c and recheck all feet



Soft foot example: pipe strain - relieve external forces



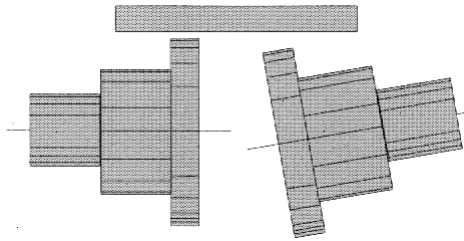
Soft foot example: squishy foot - re shim all feet with max 3 shims and recheck

Alignment methods and practices

When eliminating soft foot follow these steps:

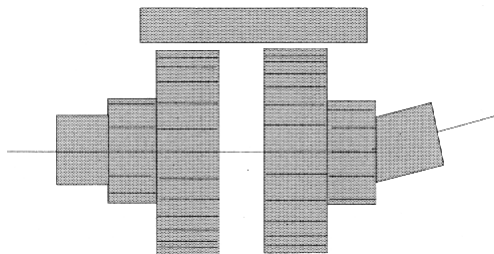
- 1) Check all four machine feet, any foot showing over 3.0 mils correct as appropriate.
- 2) Examine the largest (or two largest if the same) soft foot with feeler gauges to determine the type of soft foot. It never hurts to examine the other feet as well, but concentrate on finding and fixing the largest problem first.
- 3) Correct the condition diagnosed by shimming only one foot if any.
- 4) If all feet are within tolerance commence the alignment.

The straightedge



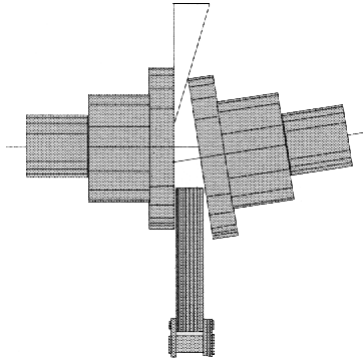
This method of shaft alignment was common practice in many plants, provided a flexible coupling was used, it was considered good enough to eyeball the alignment and bolt the machine down. The equipment is certainly cheap and readily available.

The corrective values for the machine feet were usually estimated according to the experience of the person carrying out the alignment. Most often corrections at machine feet need to be repeated on a trial and error basis before the “eyeball” alignment condition was completed. Even then there is no certainty that the completed alignment was correct. Since the resolution of the human eye is limited to 4.0 mils, alignment accuracy is correspondingly limited. Additionally without having carried out extensive checks on the fitting accuracy of the coupling on the shaft, no direct correlation between the completed alignment and the actual alignment of the machine shafts can be made.

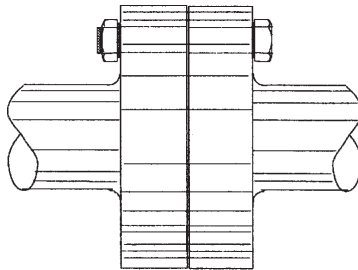


At best this alignment method can be described as coupling alignment not shaft alignment as defined earlier.

The feeler gauge



Although classified here as an “eyesight” method of shaft alignment the feeler gauge method under certain circumstances and for some machines can be perfectly acceptable. In the installation and alignment of turbine sets where the coupling half is an integral part of the rotor shaft and has no flexible elements, it is possible for a skilled turbine engineer to align the two coupling halves very accurately. (As noted in the section on alignment tolerances, no allowance for offset or gap is permissible on these “solid” type of couplings)



Using the feeler gauge or a vernier caliper the engineer accurately measures any gap between the coupling halves. Lift oil is then used to rotate the shafts together through 180 degrees and the “gap” is then checked again (with the lift oil off). This procedure is then carried out for the horizontal alignment measurements.

Alignment methods - Eyesight

Readings are usually graphically plotted to establish alignment condition and any necessary corrections that are required. In some cases engineers will rotate one shaft through 180 degrees and take additional readings, these readings are then averaged to eliminate any possible shaft machining errors. The averaged readings form the basis for the alignment graph.

On machines that employ flexible elements in the coupling design, the use of feeler gauges is beset with the same limitations as the straightedge method and can only be described as coupling alignment.

Alignment methods - Dial indicators

The use of dial indicators for the vast majority of shaft alignment tasks where a flexible coupling element is used represents a substantial step forward in accurate shaft alignment methods. There are a number of dial set ups that can be used to effect the alignment of machines, this section will review some of these, however, there are also a number of factors that the engineer should take into account before embarking on a dial indicator alignment task.



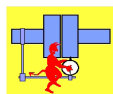
Indicator bracket sag: This should always be measured before actual alignment readings are taken - no matter how solid the bracket appears. See section on measuring sag.



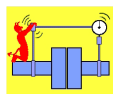
Internal friction / hysteresis: Sometimes the gauge has to be tapped in order for the indicator needle to settle on its final value.



1 mil resolution: Up to 0.5 mil rounding error may occur with each reading. This may be compounded several times in a full set of readings.



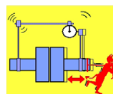
Reading errors: Simple errors occur when dials are read under difficult conditions and severe time constraints.



Play in mechanical linkage: slight amounts of play may go unnoticed but will produce large reading errors.



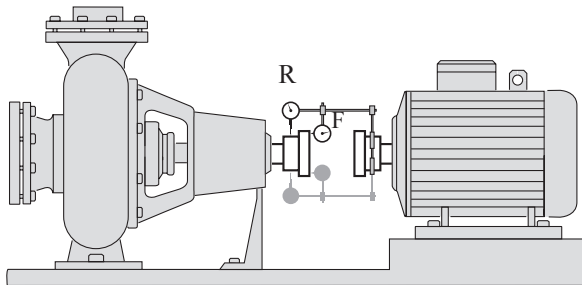
Tilted dial indicators: The gauge may not be mounted perpendicular to the measurement surface so that part of the displacement reading is lost.



Axial shaft play: This will affect face readings taken to measure angularity unless two axial gauges are used.

Rim and Face Method - By trial and error

The interpretation of shaft alignment readings using dial indicators, taking factors such as bracket sag into consideration requires an elementary understanding of maths and geometry. In some cases these skills are limited and a rough trial and error procedure is used where bracket sag and shaft float are ignored. Additionally only one shaft is rotated during the measurement adding errors to the alignment caused by coupling run-out and shaft bending.



The above sketch illustrates the scenario. Rim and face indicators touch the fixed machine coupling. Indicators are zeroed at 12 o'clock and the machine to be moved shaft is rotated through a half turn to the 6 o'clock position. The foot nearest the coupling is raised (or lowered) by an amount equal to half the rim indicator reading. Shims are repeatedly placed under the foot furthest from the coupling until the face indicator readings do not change as the shaft is rotated.

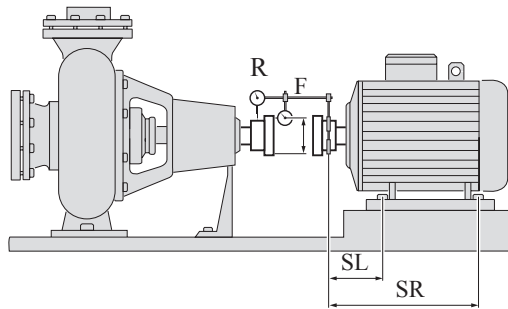
Similarly the indicators are zeroed at the 3 o'clock position and rotated to the 9 o'clock position for the horizontal correction.

It is usually easy to spot when this procedure is used as there are often a number of thin shims under the rear feet of the machine. Usually this trial and error procedure results in significant misalignment errors at the coupling transmission planes and where possible this method should be discouraged in favor of other dial or laser methods of alignment.

Alignment methods - Dial indicators

Rim and Face Method - By calculation

The measuring device for this type of alignment is a dial indicator. The dial hand indicates, or points, to increments marked on the dial face. As the foot is pushed into the body, the dial hand rotates clockwise. The number of indicator marks that the hand moves is equal to the distance that the foot was pushed into the body. When the foot travels out from the body the dial hand similarly indicates the travel distance. The dial count is positive when the foot travels in and negative travelling out.



R = Rim

F = Face

sL = Distance from the coupling center to left feet of right m'ce

sR = Distance from the coupling center to right feet of right m'ce.

Rim and Face alignment takes its name from the positions of the indicator feet during measurements. A traditional indicator set up is shown above.

Once mounted, the two shafts are rotated together and the dials are read at 12:00, 3:00, 6:00 and 9:00.

Formulas for calculating alignment corrections

For such set ups, the MTBM alignment at the plane of the indicator foot is as follows:

$$VO = (R6 - R0 - RS)/2$$

$$VA = (F6 - F0 - FS)/\text{dia}$$

$$HO = (R9 - R3)/2$$

$$HA = (F9 - F3)/\text{dia}$$

Alignment methods - Dial indicators

$$\text{Shim} = (F6-F0+FS)(s)/\text{dia} - (R0-R6+RS)/2$$

$$\text{Move} = (HA)(s)-HO$$

$$\text{Move} = (F9-F3)(s)/\text{dia} - (R3-R9)/2$$

If the dial indicators are set to zero at 12:00 and then read at 6:00, the shim calculation becomes:

$$\text{Shim} = (F6+FS)(s)/\text{dia} + R6-RS/2$$

Positive result means add shims. Negative result means remove shims.

If the dial indicators are set to zero at 3:00 and then read at 9:00 the MOVE calculation becomes:

$$\text{Move} = (F9)(s)/\text{dia} + R9/2$$

Positive means move toward 3:00

Negative means move toward 9:00

The Shim and Move calculations must each be done twice, once for the front feet, and once for the back feet.

Indicator reading validity rule.

The sum of the 3 and 9 o'clock readings should equal the sum of the 12 and 6 o'clock readings. This applies to both radial and face readings.

Alignment methods - Dial indicators

Where:

R0 = Rim reading at 12:00 o'clock position

R3 = Rim reading at 3:00 o'clock position

R6 = Rim reading at 6:00 o'clock position

R9 = Rim reading at 9:00 o'clock position

F0 = Face reading at 12:00 o'clock position

F3 = Face reading at 3:00 o'clock position

F6 = Face reading at 6:00 o'clock position

F9 = Face reading at 9:00 o'clock position

dia = Diameter of the circle travelled by face indicator foot

RS = Sag of Rim indicator

FS = Sag of Face indicator*

s = Span from measurement plane (rim indicator foot) to machine foot (front or back) This value can be positive or negative

Clockwise is determined looking along shaft from MTBM towards STAT.

$$\text{Shim} = (\text{VA}) (\text{s}) - \text{VO}$$

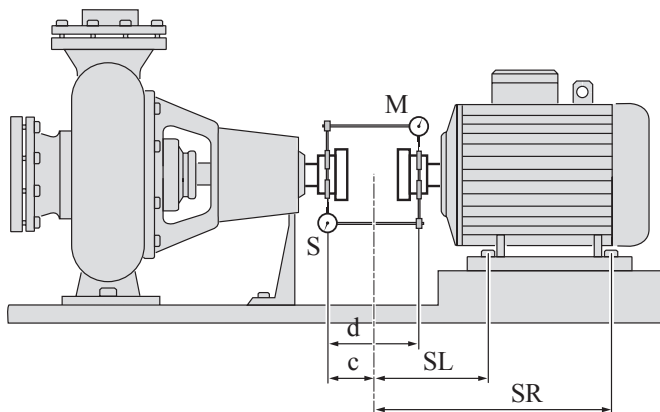
Sag

A major source of error in the above procedure is the sag of the spanner bar. This error can affect the shim amounts to such an extent that the machine will be grossly misaligned. To compensate for this sag, measure it and then add the sag reading (it can be positive or negative) to the 6:00 readings. See the above formulas.

Alignment methods - Dial indicators

Reverse indicator method - By calculation

The reverse indicator method of alignment is the most advanced dial indicator alignment method, as such it is recommended by the American Petroleum Institute (API 686) as the preferred dial indicator alignment method.



Reverse indicator alignment takes its name from the positions of the two radial indicators opposing one another on the opposite coupling halves. A traditional indicator set up is shown above. Once mounted, the two shafts are rotated together and the dials are read at 12:00, 3:00, 6:00 and 9:00.

Formulas for calculating Reverse indicator alignment

For such setups the misalignment at the coupling center is as follows:

$$VO = (S6-S0+SS)/2 - (S6-S0+SS + M6-M0-MS)C/2D$$

$$VA = (S6-S0+SS + M6-M0-MS)/2D$$

$$HO = (S9-S3)/2 - (S9-S3+M9-M3)C/2D$$

$$HA = (S9-S3+M9-M3)/2D$$

Alignment methods - Dial indicators

Where:

S0 = Left rim reading at 12 o'clock

S3 = Left rim reading at 3 o'clock

S6 = Left rim reading at 6 o'clock

S9 = Left rim reading at 9 o'clock

M0 = Right rim reading at 12 o'clock

M3 = Right rim reading at 3 o'clock

M6 = Right rim reading at 6 o'clock

M9 = Right rim reading at 9 o'clock

d = Distance between left and right indicators

c = Distance between left indicator and coupling center

SS = sag of left rim indicator (1)

MS = sag of right rim indicator (1)

(1) these values can be positive or negative

The corrections at the right machine feet can be calculated as follows:

Shim left feet = $(VA - sL) - VO$

Shim right feet = $(VA - sR) - VO$

Positive result means add shim, negative result means remove shim.

Shim left feet = $(VA - sL) - VO$

Shim right feet = $(VA - sR) - VO$

Positive result means move towards 3 o'clock, negative means move toward 9 o'clock.

sL = Distance from the coupling center to left feet of right m'ce

sR = Distance from the coupling center to right feet of right m'ce.

If the dial indicators are set to zero at 12 o'clock and then read at 6 o'clock the shim calculation are as follows:

$$HO = (S9 - S3)/2 - (S9 - S3 + M9 - M3)C/2D$$

$$HA = (S9 - S3 + M9 - M3)/2D$$

Alignment methods - Dial indicators

$$\text{shim left feet} = (S6-S3+M6-M3)(c+sL)/2D - (S6-SS)/2$$

$$\text{shim right feet} = (S6-S3+M6-M3)(c+sR)/2D - (S6-SS)/2$$

Positive result means “add shim”, negative result means “remove shim”.

If the dial indicators are set to zero at 3 o'clock and then read at 9 o'clock the move calculations are as follows:

$$\text{move left feet} = (S9+M9)(c+sL)/2D - S9/2$$

$$\text{move right feet} = (S9+M9)(c+sR)/2D - S9/2$$

Positive result means move towards 3 o'clock, negative means move toward 9 o'clock.

Indicator Bracket Sag Measurement

To measure sag mount the entire measurement fixture (brackets, bars and indicators) onto a piece of straight pipe. Adjust the fixture until the brackets are the same distance apart as they will be when they are mounted on the actual machinery. Likewise position the indicators as near possible to the way they will be set on the machinery. With the indicators held at the 12 o'clock position zero the dials. Rotate the pipe until the indicators are at 6:00 o'clock. Read and record the dial indicators (the rim indicator will be a negative value, the face indicator may be positive or negative but should be close to zero)

Alignment methods - Dial indicators

Vertical and horizontal shim corrections are shown on each graph. The corrections assume that the alignment should be 0.0/0.0 in vertical and horizontal planes. Any manufacturers figures or computed figures for thermal expansion should be accommodated in these shimming corrections or in the original dial indicator readings.

Shaft alignment by laser became popular in the mid 1980's when Prueftechnik introduced OPTALIGN®, the world's first commercially available computer aided laser shaft alignment system. Despite its then relatively high price, the system quickly gained a market popularity with mechanics and companies across a wide spectrum of process industries worldwide.

OPTALIGN offered many significant advantages in effecting quick and accurate alignment of coupled rotating machines. Since the introduction of the first system developments in laser and microprocessor technology have allowed new generations of laser systems to be developed which offer the user simple to understand, menu led, systems that can be used for virtually any shaft alignment task irrespective of complexity or size.

As we have seen in the previous sections there are a number of important considerations that should be taken into account when using mechanical methods of shaft alignment, additionally calculations of alignment corrections can be complicated and error prone. None of the considerations apply to the laser method of shaft alignment. Access to precision shaft alignment and the benefits that this brings (see following section) is readily available when laser shaft alignment is used on site.

A summary of some of the advantages offered by laser systems are shown here:

- Precision alignment with no graphical or numeric calculations to perform.
- Graphic display of alignment results at the power transmission planes of the coupling and shim and adjustment corrections at the machine feet.
- No mechanical fixtures - no bracket sag.
- No need to disassemble the coupling to effect an alignment.
- No need to take readings at predetermined locations such as 12;00, 3;00, 6;00 and 9;00 o'clock. Results can be obtained with less than 90 degrees of shaft rotation.

Laser shaft alignment

- Data storage and print out of results for report generation of alignment condition.
- Certified calibrated accuracy of the laser system to comply with ISO 9000 requirements.
- Universal bracket systems which cover all types of alignment application. No need for special “Christmas tree” brackets for long spacer shaft measurement.
- Menu driven user interface allows use by a wide range of engineering skills and disciplines.
- Live dynamic display of vertical and horizontal corrections during alignment corrections.
- Built-in alignment tolerance analysis of alignment accuracy.

Having identified some of the benefits and advantages that can be obtained by using a laser alignment system to carry out shaft alignment, it is important to establish the functionality of the alignment system that will suit the users requirements. There are a number of systems available and a number of manufacturers who offer laser alignment systems.

As a minimum the system you choose should have the following capabilities:

- **Certified calibration to a traceable standard.** There is no point purchasing a system for accurate shaft alignment that cannot have its measurement accuracy certified.
- **High accuracy and repeatability.** Poor accuracy simply results in wrong correction values. High repeatability means that fewer measurements are required to acquire sufficient data to calculate accurate results.
- **Rugged, water, shock and dust proof** A rugged enclosure means outdoor use in wet conditions is not a problem. Rugged instruments with a guaranteed seal of approval like the IP standards (see page [60](#) and [62](#)) let you continue working even in adverse conditions.

- **Measurement resume capability** Resume allows you to easily re-start an alignment in progress after an interruption or at the start of a new day the user won't have to input dimensions or targets again, even measurement results will be saved.
- **Measurement extend capability** The ability to extend the dynamic range of the laser detector system will ensure that no matter what the misalignment being measured the laser system will cope with the alignment task. Static detector systems will not allow measurement of gross misalignment on long or intermediate spacer shafts whatever the stated size of the detector plane. (See later notes).
- **Interchangeable static feet** The ability to vary static feet allows the engineer maximum flexibility and the ability to deal with bolt bound feet on the MTBM without the need for re-measuring or complex calculations; all possible alternatives of machine moves can be shown.
- **Assortment of brackets** A wide range of brackets means that measuring equipment can be fitted even to the most awkward of machines with speed and ease.
- **Tolerances (TolCheck)** Built in verification of alignment tolerances save time and effort. No time is wasted on unnecessary machine moves. Automatic tolerance check shows when excellent or acceptable alignment has been reached.
- **Report generation directly from the box** Direct reporting means faster reporting **to any printer** with the serial number, date and time, and operator name printed on the report, allowing full compliance with ISO 9000 traceability requirements for example.

Laser systems basic operating principles

Essentially there are two types of laser systems, one that uses a single beam projected onto either a detector or on to a reflector that returns the beam to the laser detector, the other type of system uses two lasers each with inbuilt detectors. The former single laser system is a patented system used exclusively by Prueftechnik, the two laser systems are employed by other system suppliers.



The single laser system as shown above has a number of advantages that have been incorporated to improve system versatility and useability.

Measurement extend capability - only one laser data means that it is possible to dynamically extend the detector range of the system to incorporate gross misalignment - see later explanation.

Split alignment capability - one laser allows alignment of machines that have no spacer or coupling in place, each machine can be rotated independently. This is particularly useful when large spacer couplings or fluid couplings are used, when aligning large machines such as turbines or when one or both machines cannot easily be rotated.

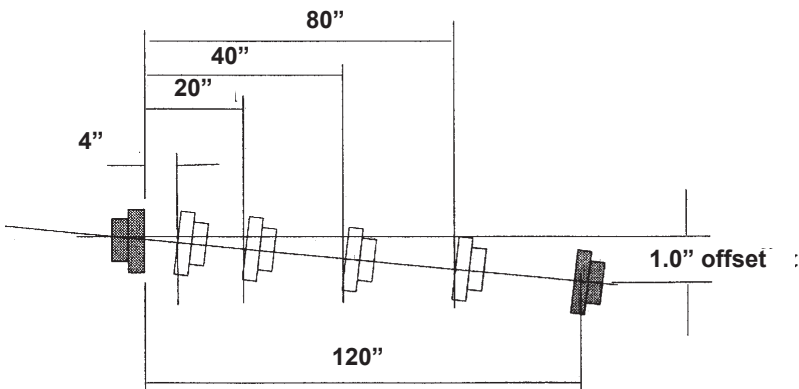
Single cable technology - Only one (or no) cable is required. This is particularly useful on long spacer shafts such as cooling tower drives where long cables can influence alignment measurements by becoming entangled during measurement.

Only one laser to adjust - On long spacer shafts or large machines set up is much easier with only one fixed datum position to adjust.

Measurement extend capability explained

Even moderate misalignment quickly causes the beam to stray out of range of even the largest detectors. Therefore it is essential that your laser system possess the ability to dynamically extend the sensor plane as needed. Large size alone in a detector is useless. Prüftechnik laser systems all possess infinitely extendible measurement range in compact stable sensor housings.

Taking as an example a cooling tower drive with a spacer shaft coupling of 120 inches. The offset between the driver and driven shafts can be substantial even with only a small angular offset between the shafts.



Laser shaft alignment

This previous sketch illustrates the limitations imposed by long spacer coupling lengths.

Taking as a simple example a coupling set up with an angular misalignment between the couplings of **0.5 degrees**, this means over a simple short coupling length of 4 inches an offset of 34.8 mils between coupling centerlines would occur. An offset that could be comfortably measured by any laser system.

If the distance between coupling faces increases to 20 inches the centerline offset becomes 174 mils, outside the range of most static laser detector systems.

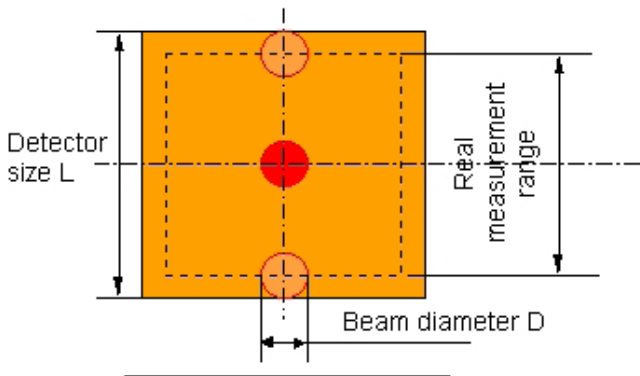
Now increase the distance to 40 inches offset = 348 mils

As the coupling spacer gets longer so does the offset until at 120 inches a massive 1.0 inch offset occurs. This with only a 0.5 degree angle between the shaft ends!

This large offset can only be measured by an extendable detector range since it would require a static detector area of approximately 2.4 inches to accommodate this offset.

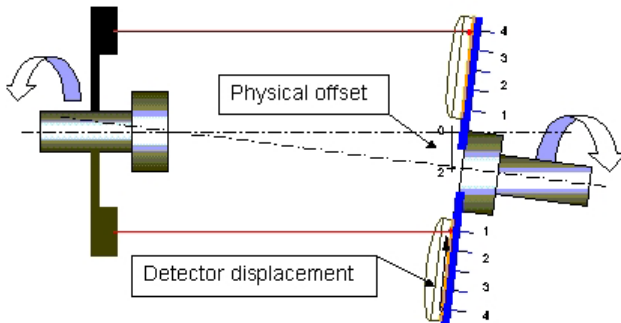
The reason for such a large detector can be explained as follows:

The working area of the detector is less than the physical detector surface. For example, if the detector area is 790 mils x 790 mils, and the laser beam is 157 mils dia then the maximum useful measurement range is 630 mils as shown below.



Laser shaft alignment

To be able to measure an offset a system detector range has to be twice the offset. As with a dial gauge, the laser receiver measures twice the physical offset of the two shafts as shown below.



To measure a physical offset of 80 mils we need a detector measurement range of 160 mils.

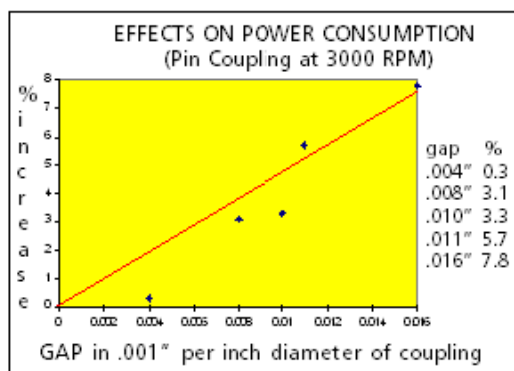
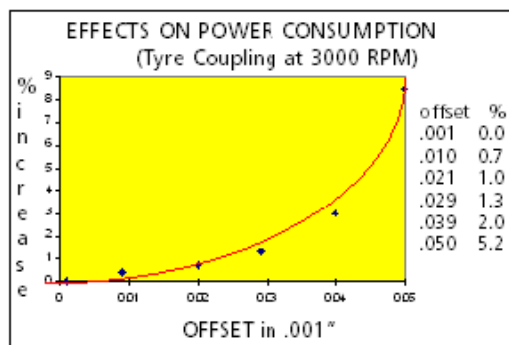
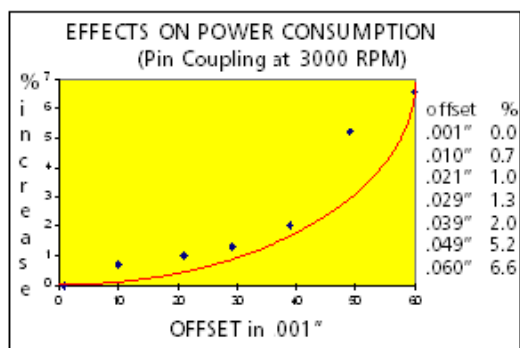
Laser Shaft Alignment Cuts Energy Costs

A project to determine the extent to which shaft misalignment influenced the power consumption of the plant was set up as a graduate student project at a major UK chemical processing plant. The study was conducted over a six week period in a controlled environment that accurately reflected the normal operating conditions across the plant.

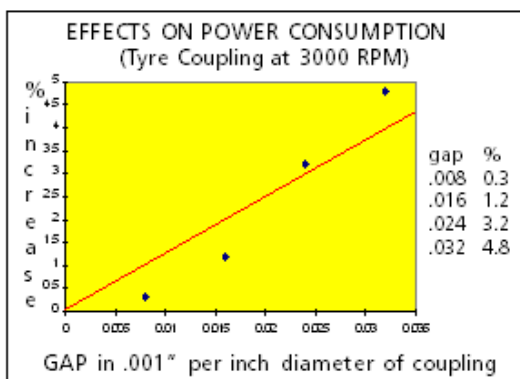
A redundant 7.5 kW pump rig in a plant was used for the investigation. Before the project commenced the pump and motor were removed to the workshop where new bearings were fitted, and both units were rebalanced to eliminate any external factor that could distort the project results. Plates and jacking bolts were attached to the motor base plate to allow fine adjustments in alignment condition. The pump set was installed to circulate water through a closed loop of piping with the motor running at 3000 RPM (+/- 1% due to variations in load condition). The pump and motor were initially installed with the alignment recorded as 0.00 gap and offset in the vertical and horizontal directions. The system was run in this condition for a number of days with current drawn being measured at the distribution board every few hours. During the course of the trial period the alignment of the machines was adjusted and at each misalignment interval run for a set period with current drawn measured at regular intervals.

Across the site the two principle types of coupling installed were “pin” and “tire” couplings. In order to obtain a reasonable picture of potential savings that could be obtained in the plant both types of coupling were installed with the same amount of misalignment/current measured on each coupling type.

The results of the study are shown in the following graphs. Offset misalignment affected power consumption more than angularity; angular misalignment affected power drawn by “pin” type couplings more than “tire” couplings. The components of misalignment are additive irrespective of whether the misalignment was vertical or horizontal.

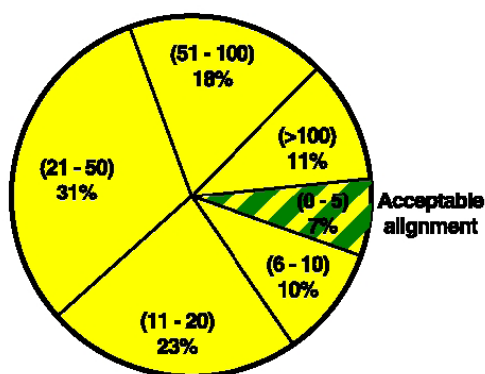


Laser shaft alignment - Case study



It was concluded from the project to implement a site wide recommendation to align machines to within an offset tolerance of 0.005 inches and an angularity tolerance of 0.0005 inches per inch of coupling diameter.

To estimate the potential cost savings that could accrue from this new site standard a random sample of machines were measured to estimate the extent of misalignment that existed on the plant. The pie chart below illustrates the findings of this survey.



Shaft offsets in 1/100 mm at the coupling center for a sample of 100 machines operating at 3000 RPM.

Laser shaft alignment - Case study

Less than 10% of machines measured were within the recommended site alignment standard.

Using the pie chart a representative median offset of 0.35 mm was estimated as a reasonable figure for calculating the potential power saving in the plant. Given that the power consumption for the rotating equipment in the plant was in the range of 30 Megawatts, the following estimate of power saving that could be achieved was:

Assuming electricity rates of \$0.06 per kWh and a conservative % power reduction of 0.75%.

$30,000 \text{ kW} \times 0.75\% \times \$0.06 / \text{kWh} = \$13.50 \text{ per hour}$

or \$101,360. – per year!

Laser shaft alignment - Case study

Laser shaft alignment improves pump reliability

Substantial plant operating improvements were achieved following the introduction of a comprehensive pump alignment and monitoring program at a major Acetate Chemical plant in Derbyshire.

The production process requires materials to be mechanically moved around the plant from process stage to process stage. Some 260 pumps are used in this plant, it is therefore vital that both duty and stand-by equipment is reliable and available. Maintenance was very much a firefighting exercise until 1996. The plant engineer at that time persuaded management of the need to take a more pro-active view of pump performance maintenance and monitoring. Using Prueftechnik laser alignment systems and condition monitoring equipment a coordinated plan to improve plant performance was introduced.

In the preceding years there had been an estimated 120 pumps repaired per year at an annual cost of some \$192,000.–, the calculated mean time between failure (MTBF) of these pumps was 10 months.

By applying a combination of laser alignment of newly refurbished machines and alignment of installed machines when time permitted plus routine plant condition monitoring together with a comprehensive review of installed components such as seals, bearings and gaskets the plant began to see significant savings on maintenance of the all important pump systems.

The program, now well established, has returned substantial dividends. Plant reliability has improved to more than 46 months MTBF and routine pump repairs have been drastically reduced.

Calculated savings are now in excess of \$157,000.– per year, and since the beginning of the program in 1996 is in the order of \$880,000!

Laser shaft alignment - Case study

A comprehensive plan of action was used by engineers to achieve these extraordinary savings in the plant, the key factors include:

- Engineer's and manager's commitment to the program
- Patience!
- [Laser Alignment](#)
- [Condition monitoring](#)
- [Training](#)
- Root cause analysis
- Careful mechanical seal selection
- Careful bearing selection
- Partnerships with suppliers
- Improved piping design and installation
- Considered pump selection
- Advanced lubrication systems selection

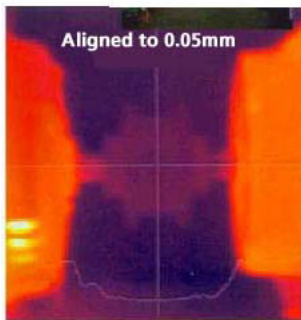
Laser shaft alignment - Case study

Laser shaft alignment improves bearing and seal life

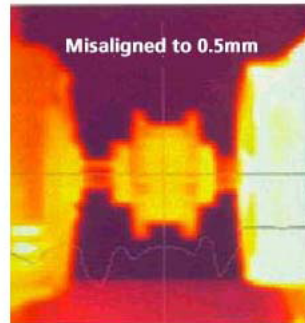
A study was conducted by the Infrasppection Institute in the USA to evaluate the effect of misalignment on key machine elements such as bearings, seals and couplings.

In a series of tests, misalignment was introduced into a pump motor set. At each new misalignment interval thermographic pictures were taken to identify the degree of temperature rise on key components.

The tests were conducted across a wide variety of flexible coupling types. Without exception all couplings, bearings and machine housings (and therefore seals) showed significant temperature rise. The graphic below shows the effect of misalignment on components when the machine set was aligned to ± 2 mils and when the misalignment was increased to $+ 20$ mils.



Aligned to ± 2 mils



Aligned to $+ 20$ mils

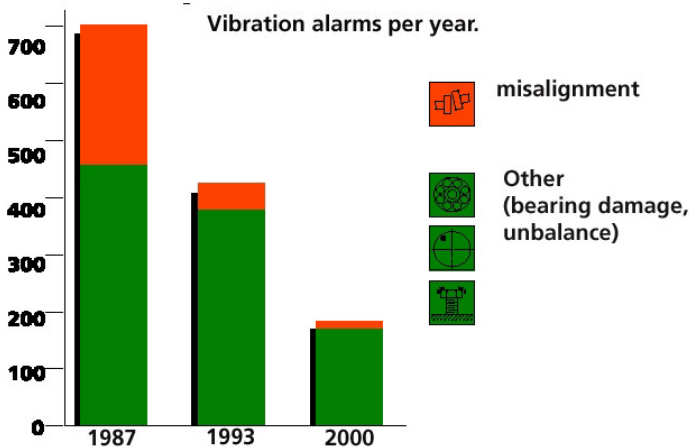
Not only was the flexible element of the coupling shown to heat up, but the machines themselves also develop elevated temperatures particularly around the bearing housings. Neither bearings nor seals are designed to operate at the elevated temperatures caused by misalignment for prolonged periods of time. An inevitable result of their operating in these conditions is premature failure and reduction in machine operating life.

Laser shaft alignment - Case study

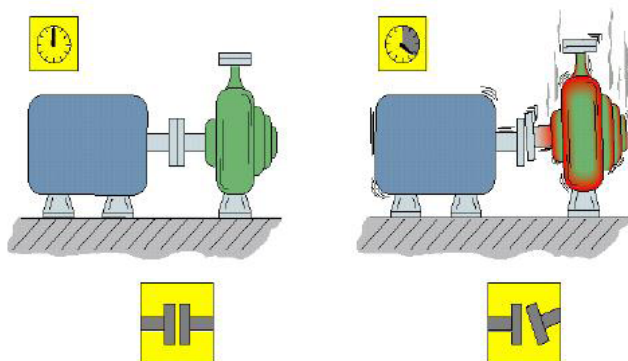
Laser shaft alignment reduces vibration alarms

During the period from 1987 to 2000 a major UK petroleum refinery adopted laser shaft alignment as a standard policy for all coupled rotating machinery. They used the Prueftechnik OPTALIGN system and later the ROTALIGN® system. Over the period they also monitored the incidents of vibration alarms and how, if at all, the use of laser shaft alignment would help reduce this. Alarms were broken down into problems caused by “misalignment” and “other” problems such as bearing damage, unbalance and mechanical looseness.

The graph provided by the company shows clearly that a substantial reduction in alarm violations was achieved, with those of alignment related problems all but eliminated altogether.



Thermal expansion of machines



In most cases in this handbook, we have considered only the cold alignment conditions of rotating machines. However, for larger machine sets and for equipment that operates at elevated temperatures on one component of the machine set it is necessary to consider the effects of expansion (or contraction) on the alignment condition of the machine. There is little point in accurately aligning a machine set at cold if this alignment condition will change at the normal operating condition of the machine set. There are a number of ways of establishing the final alignment or operating alignment condition.

- Manufacturers of machines should be able to provide thermal offset information
- Empirical calculation based on coefficient of Thermal Expansion for specific materials per unit length of centerline height per degree of thermal change (see following page).
- Online measurement of cold to hot alignment condition using contact or non contact alignment measurement instruments.

Estimating or calculating the effective alignment position change is by no means a simple operation. On complex machine systems such as compressors where there are a number of machine elements each with varying temperature gradients simple thermal growth calculations become very complex. In these cases on-line measurement of the machine components is usually necessary.

Thermal growth calculations

If the direction and extent of growth are known, the machines may be purposely misaligned such that they grow into place, resulting in good alignment condition during normal operation. **OPTALIGN Smart**, **SHAFTALIGN®** and **ROTALIGN Ultra** contain a special function designed especially to incorporate such alignment target values. The most readily available target specifications for cold alignment are generally obtainable from machine manufacturers. Where this information is not available the following calculations will assist in establishing thermal growth.

$$DL = L (c) (DT)$$

Where DL = thermal expansion
L = height centerline to base of machine
c = coefficient of thermal expansion of material
(0.0000059" for cast iron)
DT = change in temp from ambient

For example:

A pump with liquid at 300°F.
Base to center height 26 inches.
Ambient temp 50°F.

$$DL = L (a) (DT)$$

$$DL = 26 \text{ inches } (.0000059) \times (300-50)$$

$$= 26 \text{ inches } (.0000059) \times 250 = .038 \text{ inches}$$

*(Some advanced laser alignment systems such as **ROTALIGN Ultra** perform these calculations for you)*

Thermal expansion of machines

In these cases, a laser system such as the Prueftechnik **PERMALIGN®** system is an ideal tool. Systems such as **PERMALIGN** are designed for long term operation in difficult conditions, often the very act of mounting the equipment onto a turbine or compressor operating in excess of 572 degrees F will mean that the measurement system needs to be cooled to avoid damage or inaccurate thermal growth readings.

Thermal expansion is not however the only cause of machine position change. Many elements can impinge on the accuracy of the final result such as:

- Thermal Expansion of bearing supports
- Changes in radial or axial forces
- Changes in oil film thickness on bearings
- Changes in foundation or base plate supports
- Changes in piping forces.

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